Clustered CDMA ad hoc networks without closed-loop power control

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CLUSTERED CDMA AD HOC NETWORKS WITHOUT CLOSED-LOOP POWER CONTROL

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ABSTRACT

This paper develops a system design for clustered wireless ad hoc networks, combining CSMA and CDMA to enable spatial reuse and simultaneous transmissions. Typically, CDMA networks require fine-tuned power control, but here that requirement is eliminated through a combination of open loop power control, user ordering, and successive interference cancellation (SIC). A network topology with high network awareness via a broadcast CSMA channel is developed. The resulting system increases network throughput and overcomes existing problems with IEEE 802.11.

INTRODUCTION

Wireless ad hoc networks, characterized by the lack of wired infrastructure, pose unique challenges in the multiple access design. Extensive research exists on code division multiple access (CDMA) for cellular systems. The multiple access capability, capture, and anti-multipath capability of spread spectrum are the main reasons that CDMA is the dominant choice for the physical layer of third generation cellular systems. Despite notable recent work [1] [2], stringent power control requirements in the absence of central infrastructure are still a primary reason why CDMA has not been exploited at the physical layer of ad hoc networks. The physical layer in IEEE 802.11 uses carrier sense multiple access with collision avoidance (CSMA/CA) and supports only one transmission at a time within a transmission range. A successful packet transmission happens only when one packet appears in a time slot. In a dense network, this results in low spectral efficiency and causes fairness issues in a multi-hop network [3], and becomes more serious in a dense network [4].

Fast inner loop power control is impractical for wireless ad hoc networks for two reasons. First, there is no centralized authority to coordinate the required power levels. Secondly, the required power level for a given node will change suddenly as it communicates with different nodes that may have dramatically different channels. These highly variable channels result from three primary causes [5]: obstructing objects, distance-dependent path loss, and small-scale Rayleigh fading. In this paper, we propose a simple open-loop method to compensate for the first two effects, and the rapid Rayleigh fading is compensated for by ordering users and using SIC [6] at the receiver. Preliminary work done in [7] shows that under fading, performance of a CDMA system incorporating SIC is comparable to that of a conventional CDMA receiver using ideal power control. However, their approach assumes perfect channel estimates. In this paper, we present an approach which incorporates SIC for ad hoc networks in the presence of imperfect channel estimates [8], and adapt it to an ad hoc network.

SIC is a nonlinear type of multiuser detection (MUD) shown in Fig. 1 in which users are decoded successively [6], [7], [8]. The approach successively cancels the strongest remaining user, k, by re-encoding (with PN sequence c_k) the decoded bits, $\hat{b_k}$ and after making an estimate of the channel, the interfering signal, z_k is generated at the receiver. This is then subtracted from the received waveform, $y(t)$. In this manner later users do not encounter multiple access interference (MAI) caused by previous users. SIC improves performance for all users: initial users improve because the later users require less power which means less MAI for the initial users, and later users improve because early users' interference has been cancelled out. The main reason behind SIC's desirability is its low complexity and in its simplest form, SIC uses decisions produced by single-user matched filters.

To mitigate the near-far problem in CDMA, successive decoding by user ordering was also suggested in [9]. However, known symbols (training) were required for the least-squares detection to work. In [10], the performance of ad hoc and cellular CDMA networks are compared. Ad hoc CDMA networks can outperform cellular networks when the traffic is low but are found to have decreasing performance as the spreading gain is increased, which suggests that CDMA may not be profitable for ad hoc networks. However, in [11], it was

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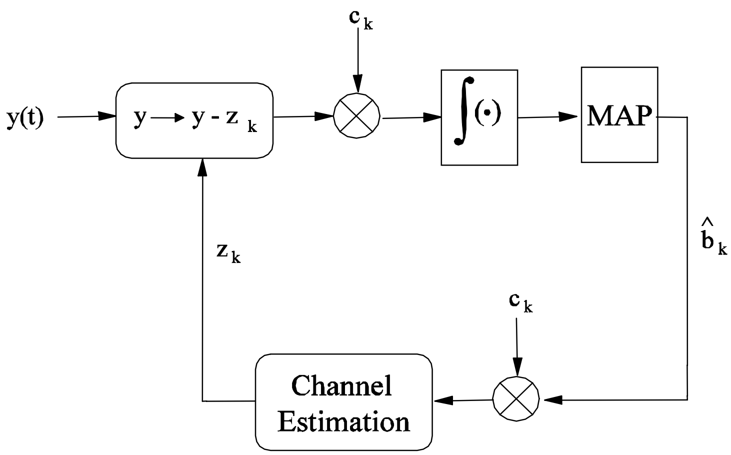

Fig. 1. (U) Successive Interference Cancellation Scheme

found that the best rate capacity region for ad hoc networks is for CDMA with successive interference cancellation, and that power control does not help the capacity significantly if the rate is already adapted. We extend these recent results with the system design in this paper.

Mobility presents a serious problem to ad hoc networks because of the instability in the topology caused by motion. The advantage of clustering as explained in the next section is to stabilize the network topology and to perform effective power control as shown in [12]. However, clustering in our paper uses a separate broadcast channel (CSMA) in addition to an uplink and a downlink CDMA channel. The combination of multi-channel spread spectrum and CSMA/CA was also proposed for sensor radio networks in [13]. However, in our approach the CSMA channel not only facilitates CDMA and SIC but is also used for network awareness among the surrounding nodes.

In the last section, analytical results, validated with simulations, are presented to show the average bit-error rate (BER) for a Rayleigh fading channel without closed loop power control for a CDMA system using SIC. This is compared with BER for a conventional CDMA system with ideal power control. It is shown that the proposed system performs better in a dense network.

AD HOC CDMA WITH CLUSTERS

In this section, hierarchy is introduced into the ad hoc network in the form of clusters, as seen in Fig. 2. Mobile nodes are grouped into clusters and each cluster has a clusterhead, i.e. A, B, C. A clusterhead can control a group of ad hoc hosts known as plebe nodes, i.e. 1,2,4,8,9,10,11. Plebe nodes can only communicate to its clusterhead. Gateway nodes, e.g. 3,5,6,7, are nodes that are within communication range of two or more clusterheads and relay messages between different clusters. While this grouping makes the system less "ad hoc" and more like a cellular system without wired base stations, it is an effective method for organizing an ad hoc network and providing well-defined uplinks and downlinks to avoid the transmit/receive duplex problem: users may not transmit and receive at the same time and in the same frequency.

The proposed network organization is loosely based on the Cluster Gateway Routing Protocol (DSCR) [14]. However, it features a few distinctive improvements and modifications tailored to support and capitalize on the strengths of CDMA. Nodes in the network conduct communication via three disjoint frequency channels: CDMA data uplink and data downlink channels and a broadcast CSMA control channel. The CDMA channel is primarily used for data transfer, while the CSMA channel is used for three purposes: facilitating MAC for data transfer, enabling effective open loop power control and, overcoming code assignment problems in ad hoc CDMA network as highlighted in [15].

In the downlink, all communication to plebe nodes is conducted through the clusterhead. Hence, the clusterhead has a great deal of control and can use scheduling (TDMA), or assign optimum relative weights to the users and let the plebes use SIC to decode the packets of interest (ignoring the packets intended for other nodes in the cluster). In the uplink, all plebes have a different channel to the clusterhead and send data asynchronously. In the absence of closed loop power control, the dynamic range of received signal strength at clusterhead from various plebe nodes would be high. This near-far problem in the uplink is detrimental to the performance of a CDMA system. However, as shown in the last section, the near-far problem can be mitigated by SIC and used to the advantage of an ad hoc network.

The control channel is also used to perform cluster management, routing and mobility control using CSMA. Our protocol does not require global time synchronization among all nodes in the network. Cluster-wise time synchronization is achieved by having each clusterhead to send out periodic synchronization pulses such that all mobile nodes within the same cluster can lock in the pulses and synchronize their transmissions with respect to their clusterhead.

OPEN LOOP POWER CONTROL

In a conventional CDMA network, the transmit power levels of all the plebes would have to be coordinated such that they are all received with the same power at the clusterhead. The received power at the clusterhead can be described by the following path loss equation which also takes into account shadowing and Rayleigh fading:

$$P_r = \rho^2 10^{-\zeta/10} \bar{P} \frac{P_t}{r^\alpha} \tag{1}$$

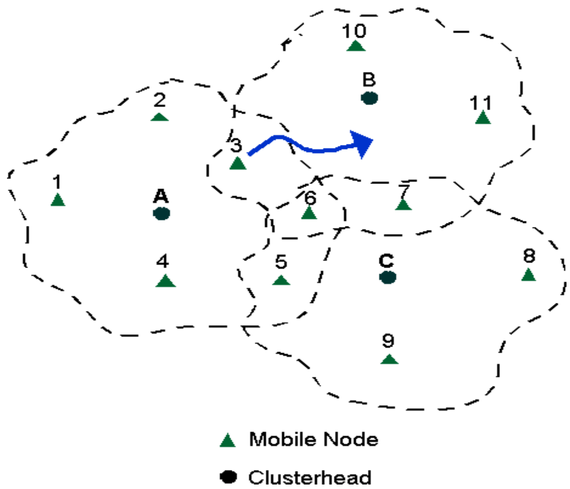

Fig. 2. (U) Sample clustered network topology

where P_r is the received power, ζ models the log-normal shadowing and hence is a Gaussian random variable with zero-mean and variance σ^2, $\bar{P}$ is a constant which is the received power at a distance of 1 meter, P_t is the transmit power, r is the distance between the communicating nodes, α is the path loss exponent and ρ is the fading amplitude assumed to be Rayleigh distributed with unit mean square value, i.e., its pdf given by

$$f(x) = 2xe^{-x^2}. \tag{2}$$

The open loop power control can be performed similar to the algorithm proposed in [12]. However, the initialization pilot signals (packets) and the clusterhead pilot power control signal are transmitted on the broadcast CSMA channel. Therefore, by monitoring pilot signals on the CSMA channel, a node can estimate the required transmission power level for the data packets on the CDMA channel – this is open loop power control.

INTRA-CLUSTER COMMUNICATION

Communication within a cluster must always go through the clusterhead as shown in Fig. 2; this protocol essentially forbids member nodes to communicate directly although they may be well within the transmission range of each other. Since the clusterhead is one hop away from all of its member nodes, any communication within the cluster is either two-hop or one hop (when the clusterhead is the final intended receiver). Communications from node to clusterhead are preceded with the typical RTS-CTS handshake on the broadcast channel as shown in Fig. 3 and followed by acknowledgement (ACK) message on successful reception. On the downlink, all nodes listen and decode all packets from their clusterhead and if successful in forwarding to the intended next-hop clusterhead, the node would send a positive acknowledgement (ACK) message to its clusterhead.

ROUTING AND MEDIUM ACCESS INFORMATION

The clusterheads together form a top-level network that exchange routing information using existing routing protocols. For simplicity Destination Sequenced Distance Vector (DSDV) is the basis for the proposed routing scheme.

In addition to a routing table, each clusterhead maintains a membership table which consist of all nodes belonging to its cluster, and a forwarding table that temporarily caches the clusters in which its recent ex-member nodes moved into for interim packet forwarding purposes. Clustering and forwarding tables are two modifications to the DSDV protocol that aim to reduce the frequency and overall size of routing messages. Instead of maintaining routing information at every node to every other nodes in the network, clustering gives us the advantage of associating a group of nodes with a clusterhead by associating the membership table of each cluster to the respective entries in its routing table.

Further, unlike the traditional DSDV protocol where routing updates occur with any topology change, there are only two types of routing updates. The first type of routing updates are triggered by the addition and deletion of a clusterhead, rather than any node. The second type of routing update is periodic, and serves to update the membership table entries in the routing tables at all clusterheads.

INTER-CLUSTER COMMUNICATION

A packet sent by a node is first routed to its clusterhead, and then the packet is routed from a clusterhead to a gateway node to another clusterhead, and so on until the clusterhead of the destination node is reached. As shown in Fig. 2, nodes within transmission range of multiple Clusterheads (nodes 3, 5, 6, and 7 in Fig. 2) are called gateway nodes.

However, clusterheads have flexibility in keeping track of the gateway nodes in its cluster. As an implication of our open loop uplink power control algorithm, each mobile node monitors all downlink messages by reading the header of each message that includes the transmission power level, final intended destination, next-hop cluster and next-hop intermediate gateway node. If the clusterhead does not keep track of its gateway nodes, it can choose not to specify an intermediate gateway node, in which case all nodes that have direct links to the clusterhead of the next-hop cluster will attempt to forward the message. The next-hop clusterhead will only grant one of the mobile nodes the permission to send by selecting the node that has the strongest channel at the time of transmission.

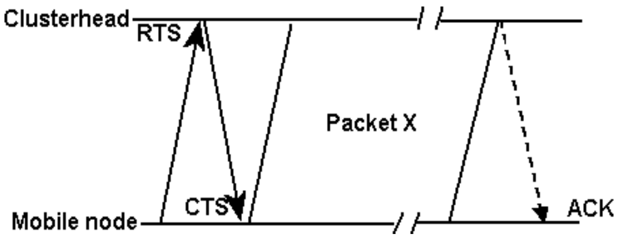

Fig. 3. (U) Member node-to-CH communication handshake

Alternatively, if a clusterhead does keep track of its gateway node, it can request a specific gateway node to forward the message to the next-hop cluster.

ADVANTAGE OF CLUSTERING OVER FLAT NETWORK

Here we consider a scenario to highlight the strength of clustering for multi-packet transmissions in a dense network over a flat network topology using CSMA/CA. Suppose in Fig. 3 nodes 1 and 3 have two packets each for nodes 2 and 4 respectively. In a flat network while node 1 is transmitting a packet to node 2, node 3 can transmit during that time only if it is sufficiently away from node 2. If the distance between node 1 and 2 is r, then node 3 should be at lease $(1+\triangle)r$. The quantity $\triangle > 0$ depends on the node density and is usually modelled as 1 in a typical 802.11 network. Therefore, considering fixed size packets, 4 time slots would be required before nodes 2 and 4 receive two packets each.

In a clustered network both nodes 1 and 3 would send one packet each to the clusterhead A, in the second time slot, A would receive two more packets and would also transmit one packet each to node 2 and 4. A would require an additional time slot to complete the transmission. Thus a total of 3 time slots would be needed as compared to 4 for a flat network. It may be noted that this improvement is very specific to the generated traffic and the location of the nodes, but the purpose is to highlight the strength of cluster topology. This reinforces the proposal in [4]; that grouping nodes into small clusters not only improves capacity but also reduces the consumed transmission power.

SIC WITHOUT CLOSED LOOP POWER CONTROL

In the uplink, the received power at the clusterhead from the transmitted signal at plebe nodes can be described by (1). It may be noted that the same set of equations is applicable at a plebe node in the downlink if the clusterhead assigns relative weights to the users. This would also facilitate the plebe nodes in mitigating other-cell interference.

Given the received Rayleigh amplitudes ρ_k for the K users, we order the received users at the node in order of their

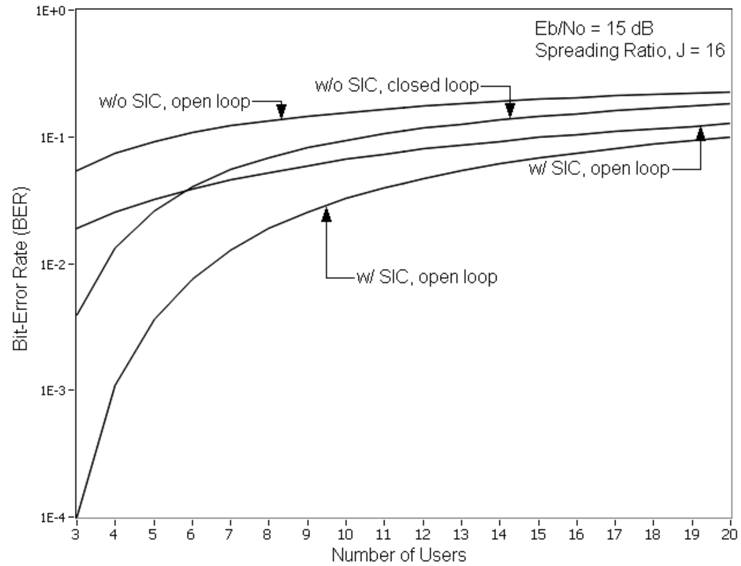

Fig. 4. (U) Analytical results: Avg BER under Rayleigh fading

received amplitudes. We define user 1 such that $\rho_1 > \rho_j \ \forall\ j \neq 1$. For BPSK, and assuming that after each interference cancellation stage there is a fraction ϵ_k of user k's energy remaining, due to the error in channel estimates, the BER expression for user k is as follows:

$$P_{b,k} = Q\left(\sqrt{SINR}\right) \tag{3}$$

Evaluating the SINR for a node using CDMA system with SIC, and imperfect cancellation, yields:

$$P_{b,k} \simeq Q\left(\sqrt{\frac{\rho_k^2 \cdot J}{\sum_{i<k} \epsilon_i \rho_i^2 + \sum_{i>k} \rho_i^2 + 1/SNR}}\right) \tag{4}$$

where J is the spreading factor or processing gain and SNR is the average signal to noise ratio. Typically, in CDMA systems, the $1/SNR$ term is insignificant, as the system performance is limited primarily by the multiple access interference. The above expression assumes that log normal shadowing and path loss have been compensated by open loop power control.

PERFORMANCE AS A FUNCTION OF NUMBER OF NODES

To observe the effect of the total number of nodes on the BER performance on the proposed system, we consider user densities ranging from 3 to 20 nodes. The average probability of error is then obtained as the average of the BER resulting from all stages of cancellation. Average BER rates obtained are shown in Fig. 4. It can be seen that when the number of nodes is greater than 6, SIC with open loop power control starts performing better then a closed loop power control system without SIC under Rayleigh fading. Therefore, for a dense network it can be concluded that under fading SIC without power control is better than a conventional receiver, even with perfect power control. The conclusions are similar to [7], but as highlighted earlier, we have taken into consideration cancellation errors resulting from imperfect channel estimates. It is assumed that the fractional cancellation error ϵ_k is about 10%, because for indoor applications in an ad hoc networks with low mobility the fading amplitude does not change much over the length of packet duration. This allows better channel estimation and reduces cancellation error [16].

EFFECT OF POWER IMBALANCE ON SIC

The performance of SIC as a function of power imbalance at the receiver was shown in [7] and an optimum power distribution in the presence of imperfect channel estimates was derived in [8], which required fast closed-loop power control [17]. In the absence of closed loop power control, the power imbalance caused by fading can be exploited at the receiver by ordering users by their received power. The received power vector for K users in the absence of closed loop power control would be suboptimal as compared to [8], but can be thought of as a loose curve fit to the optimal distribution – with the fit growing tighter as the number of nodes increases. This might cause higher BER for later nodes, as their received power could drop below the required SINR. Therefore, an upper bound needs to be determined in the level of power imbalance for SIC to work properly. However, we propose that during RTS-CTS handshake, if the channel is extremely poor and outside the level of power imbalance which SIC can exploit, then nodes may choose not to transmit and must contend for the transmission at a later time.

Again we would like to highlight that in the downlink if relative weights are assigned to the users, then the optimum power distribution can be achieved, since all the transmissions are originate from the clusterhead.

PERFORMANCE OF A 12 NODE AD HOC NETWORK

The BER is obtained for a $K = 12$ node system using SIC with a spreading ratio of $J = 16$. Results show that the proposed open loop system with SIC performs better than a comparable system with fast closed-loop power control without incorporating SIC, but not as well as a SIC system with optimum power levels. This can be seen in Fig. 5 which shows bit error rate (BER) for each node for four different CDMA systems. At the receiver nodes are ordered so that node one has the highest received power. This improvement is because of the ability of SIC to exploit unequal received power amongst active users as was shown in [8]. Since closed loop power control is not used, all the nodes do not have

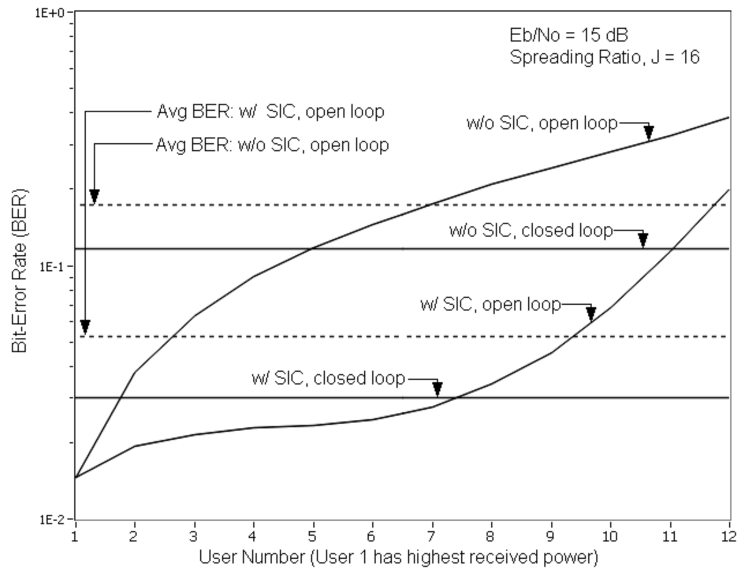

Fig. 5. (U) Comparison of BER for different CDMA systems

a consistent quality of service as is the case for systems incorporating perfect power control. This can be seen in Fig. 5, where initial nodes have a lower BER then later nodes. However, the average system performance is better then a conventional system. Note that coding is not taken into consideration here, so the BER would be further lowered by using efficient coding as was done in simulation.

SIMULATION RESULTS

In order to validate the above results, a simulation with 3 to 20 nodes was developed in LabVIEW. The system model chosen for our simulation is based on the model in [8]. The reason for choosing such a model is to incorporate a strong error-correcting code (ECC) [6]. In addition to the normal performance enhancement from ECC, an additional advantage in SIC systems is that the BER is driven low, so no error propagation occurs in the interference cancellation process. Therefore, virtually all the cancellation error is from amplitude and phase estimation error, i.e. channel estimation error. It is assumed for the two systems with perfect closed loop power control that the channel is an additive white Gaussian noise (AWGN) channel. For the other two systems, which incorporate only open loop power control, the channel is assumed to be a Rayleigh fading channel where every packet from each node undergoes an independent fading channel. However, we assume the fading amplitude remains constant within a packet duration [18]. Again the performance for the average BER against the number of nodes was determined for the four different CDMA systems. It can be seen in Fig. 6 that when total number of users is in the range of 10, SIC with open loop power control starts performing better then a conventional receiver with ideal power control. This conforms

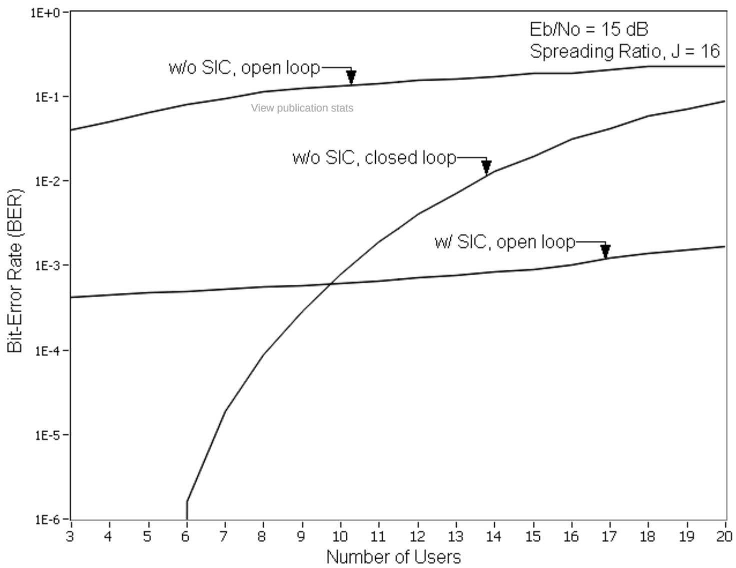

Fig. 6. (U) Simulation results with ECC: Average BER

to the results found analytically, with the improvement in the BER for all three cases in Fig. 6 due to the effective error control codes. With the addition of closed loop power control, SIC with ECC has an extremely low BER of the order of 10^{-8} for all the 12 nodes, and is therefore not plotted.

CONCLUSIONS

An ad hoc CDMA network using cluster topology is proposed in this paper to provide higher spectral efficiency, universal spatial reuse and high robustness to packet collisions. The normal CDMA requirement for closed loop power control is eliminated through a combination of open loop power control, user ordering, and successive interference cancellation. Both analytical and simulation results show that as the number of co-located nodes increases to the range of 6-10, the proposed scheme performs better then a conventional CDMA system with ideal power control under Rayleigh fading. We also show that unlike the IEEE 802.11 physical layer, multiple transmissions can take place simultaneously, at the expense of lowered spectral efficiency per transmission. Quantifying the capacity tradeoff between CSMA and CDMA is an area for future work.

REFERENCES

[1] T. ElBatt and A. Ephremides, “Joint Scheduling and Power Control for Wireless Ad-hoc Networks,” in *IEEE INFOCOMM*, 2002.
[2] S. Agarwal, S. V. Krishnamurthy, R. H. Katz, and S. K. Dao, “Distributed power control in ad-hoc wireless networks,” in *Proc. IEEE PIMRC*, Oct. 2001.
[3] S. Xu and T. Saadawi, “Does the IEEE 802.11 MAC protocol work well in multihop wireless ad hoc networks?” *IEEE Comm. Magzine*, pp. 130–7, June 2001.
[4] P. Gupta and P. R. Kumar, “The Capacity of Wireless Networks,” *IEEE Trans. on Info. Theory*, vol. 46, no. 2, pp. 388–404, Mar. 2000.
[5] T. S. Rappaport, *Wireless Communications*, Prentice Hall, - Upper Saddle River, NJ, 1996.
[6] A. J. Viterbi, “Very low rate convolutional codes for maximum theoritical performance of spread-spectrum multiple-access channels,” *IEEE J. on Sel. Areas in Comm.*, vol. 8, no. 4, pp. 641–9, May 1990.
[7] P. Patel and J. Holtzman, “Analysis of a simple successive interference cancellation scheme in a DS/CDMA system,” *IEEE J. on Sel. Areas in Comm.*, vol. 12, no. 5, pp. 796–807, June 1994.
[8] J. Andrews and T. Meng, “Optimum Power Control for Successive Interference Cancellation with imperfect Channel Estimation,” *IEEE Trans. on Wireless Comm.*, vol. 2, no. 2, pp. 375–83, Mar. 2003.
[9] Q. Zhao and L. Tong, “Semi-blind collision resolution in random access wireless ad hoc networks,” *IEEE Trans. on Signal Processing*, vol. 48, no. 10, pp. 2910–20, Oct. 2000.
[10] J. Bao and L. Tong, “A performance comparision between ad-hoc and centrally controlled CDMA wireless LANs,” *IEEE Trans. on Wireless Comm*, vol. 1, no. 4, pp. 829–41, Oct. 2002.
[11] S. Toumpis and A. J. Goldsmith, “Capacity regions for wireless ad hoc networks,” in *Proc. IEEE Inter. Conf. on Comm.*, New York, May 2002.
[12] T. J. Kwon and M. Gerla, “Clustering with power control,” in *Proc. IEEE MILCOM Conf.*, Nov. 1999.
[13] C. Guo, L. C. Zhong, and J. M. Rabaey, “Low power distributed MAC for ad hoc sensor radio networks,” in *Proc. IEEE GLOBECOM*, Nov. 2001.
[14] C. C. Chiang, H. K. Wu, W. Liu, and M. Gerla, “Routing in clustered multihop mobile wireless networks with fading channel,” in *Proc. IEEE Int. Conf. on Networks*, June 1997.
[15] M. B. Pursley, “The role of spread spectrum in packet radio networks,” in *Proc. of IEEE*, Jan. 1987.
[16] A. Hasan and J. Andrews, “Cancellation Error Statistics in a CDMA System using Successive Interference Cancellation,” in *Proc. Allerton Conf. on Comm., Cont., and Comp*, 2003, submitted to.
[17] A. Agrawal, J. Andrews, J. Cioffi, and T. Meng, “Power Control for Successive Interference Cancellation with Imperfect Cancellation,” in *Proc. Int. Conf. on Comm.*, New York, NY, 2002, pp. 356–60.
[18] E. Walker, H.-J. Zepernick, and T. Wysocki, “Fading measurements at 2.4 GHz for the indoor radio propagation channel,” *IEEE Int. Zurich Seminar on Broadband Comm.*, pp. 171–6, Feb. 1998.